Exotic Heavy Quark Spectroscopy – Theory Interpretation vs Data

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TU Dortmund

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Beauty 2013

Exotica

Belle & others [Zupanc et al. 09] , [Bondar et al., PRL 12] , [Liu et al., 13] , [Ablikim et al., 13]

State	M (MeV)	Γ (MeV)	J^{PC}	Decay Modes	Production Modes	Also observed by
$Y_s(2175)$	2175 ± 8	58 ± 26	1^{--}	$\phi f_0(980)$	e^+e^- (ISR) $J/\psi \to \eta Y_s(2175)$	BaBar*, BESII
$X(3872)$	3871.4 ± 0.6	< 2.3	1^{++}	$\pi^+\pi^- J/\psi$, $\gamma J/\psi$,$D\bar{D}^*$	$B \to KX(3872)$, $p\bar{p}$	BaBar CDF, D0
$Z(3900)$	3899 ± 6	46 ± 22	1^+	$\pi^\pm J/\psi$	$Z(4260) \to Z(3900)\pi$	BESIII*
$X(3915)$	3914 ± 4	28^{+12}_{-14}	$0/2^{++}$	$\omega J/\psi$	$\gamma\gamma \to X(3915)$	
$Z(3930)$	3929 ± 5	29 ± 10	2^{++}	$D\bar{D}$	$\gamma\gamma \to Z(3940)$	
$X(3940)$	3942 ± 9	37 ± 17	$0^{?+}$	$D\bar{D}^*$ (not $D\bar{D}$ or $\omega J/\psi$)	$e^+e^- \to J/\psi X(3940)$	
$Y(3940)$	3943 ± 17	87 ± 34	$?^{?+}$	$\omega J/\psi$ (not $D\bar{D}^*$)	$B \to KY(3940)$	BaBar
$Y(4008)$	4008^{+82}_{-49}	226^{+97}_{-80}	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^- (ISR)	
$X(4160)$	4156 ± 29	139^{+113}_{-65}	$0^{?+}$	$D^*\bar{D}^*$ (not $D\bar{D}$)	$e^+e^- \to J/\psi X(4160)$	
$Y(4260)$	4264 ± 12	83 ± 22	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^- (ISR)	BaBar*, CLEO
$Y(4350)$	4361 ± 13	74 ± 18	1^{--}	$\pi^+\pi^- \psi'$	e^+e^- (ISR)	BaBar*
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$Z(4430)$	4433 ± 5	45^{+35}_{-18}	?	$\pi^\pm \psi'$	$B \to KZ^\pm(4430)$	
$Z_b(10610)$	$10,607 \pm 2$	18.4 ± 2.4	1^+	$\pi^\pm h_b(1,2P)$, $\pi^\pm \Upsilon(1,2,3S)$	$Y_b/\Upsilon(5S) \to Z_b(10610)\pi$	
$Z_b(10650)$	$10,652 \pm 2$	11.5 ± 2.2	1^+	$\pi^\pm h_b(1,2P)$, $\pi^\pm \Upsilon(1,2,3S)$	$Y_b/\Upsilon(5S) \to Z_b(10650)\pi$	
$Y_b(10890)$	$10,890 \pm 3$	55 ± 9	1^{--}	$\pi^+\pi^- \Upsilon(1,2,3S)$	$e^+e^- \to Y_b$	

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Light states [PDG] :

$a_0(980)$ in 1965, $\sigma(600)^{\text{now } 500}$ in 1972, $f_0(980)$ in 1979, $\kappa(980)$ in 1997
discussion reopened: ['t Hooft, Isidori, Maiani, Polosa, Riquer, PLB 08]

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focus here:

$Z_c(3900)$

$Y_c(4260)$

$Z_b(106XX)$

$Y_b(10890)$

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3 weeks old
[talk yesterday by Yaqian Wang]

last weeks of Belle

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Molecules & Tetraquarks

Most prominent explanations of exotica

Pion exchange ↷

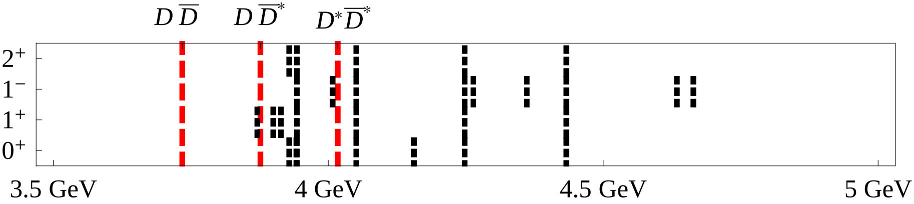
- **Mass:** E_{binding} few MeV; Masses below corresponding 2 meson threshold
- **Width:** educated guess: size similar to constituent mesons or $\mathcal{O}(E_{\text{binding}})$ → narrow

Gluon exchange ↷

- **Mass:** E_{binding} $\mathcal{O}(\Lambda_{\text{QCD}})$; Masses vary
- **Width:** typical hadronic decay width

But also: not understood QCD effects (rescattering, threshold effects,. . .) & gluonic excitations

$c\bar{c}$ Masses Theory vs Experiment



- - - measured exotica

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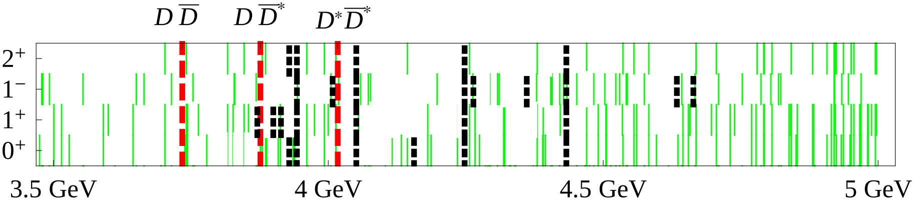

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—— molecule masses (illustrative combination from [PDG])

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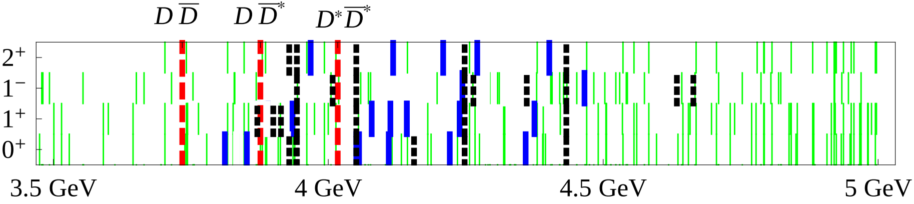

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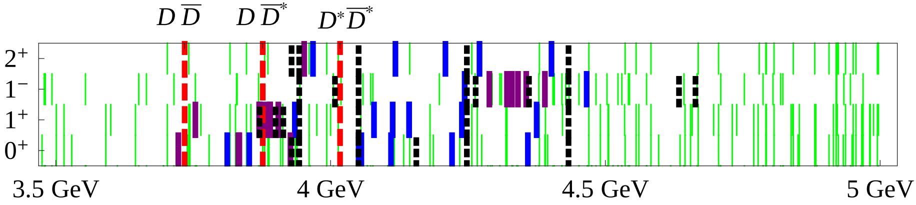

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—— constituent quark model (effective hamiltonian fixed from common hadrons)
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…(QCDSR tetraquark estimates (not shown) also not consistent)

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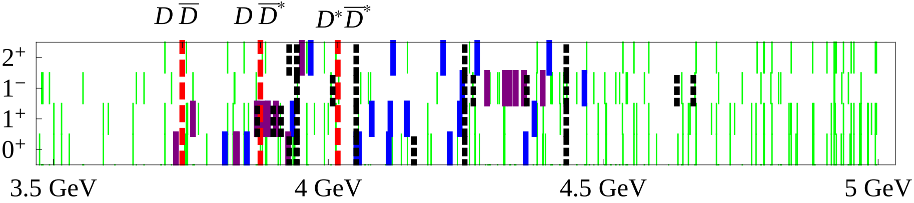

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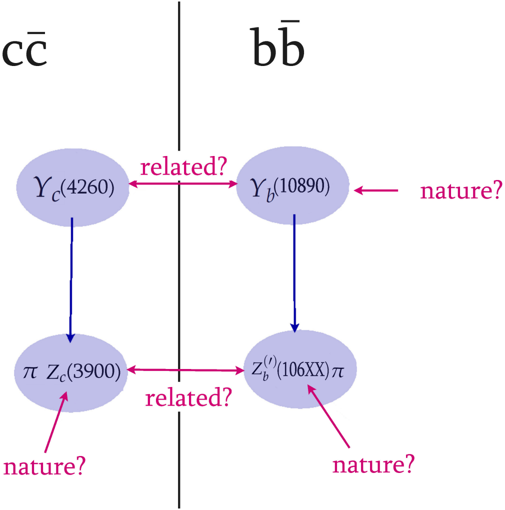
→ messy! - no model independent studies

↳ find relations & look at decays

Relation $c\bar{c}$ & $b\bar{b}$



- Understanding heavy exotica means to understand both sectors!
- Only 3 candidates in $b\bar{b}$ → this is a key puzzle!

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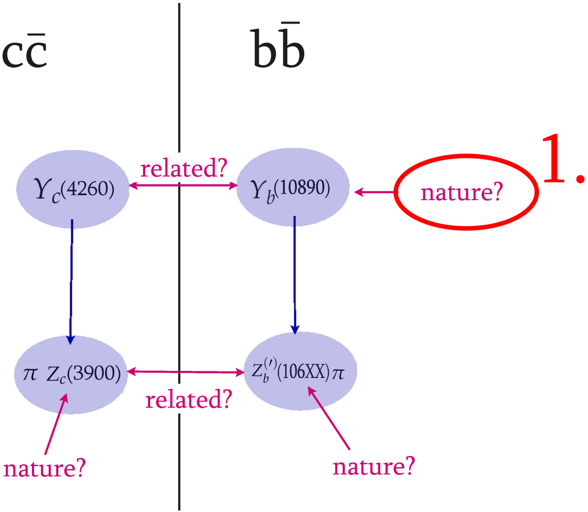

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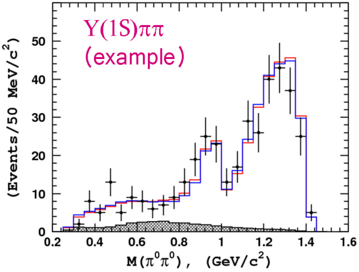
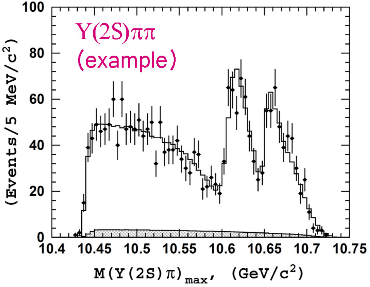
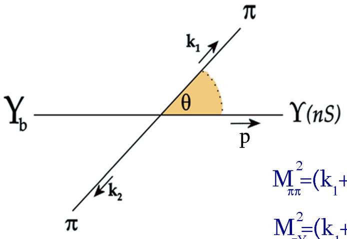
Why is the data @Υ(5S) anomalous?





[Belle Collaboration (2012)]

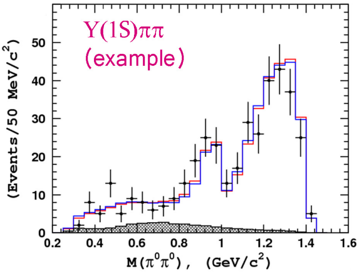


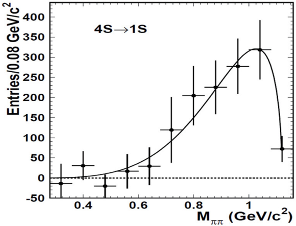
$M_{\pi\pi}^2 = (k_1 + k_2)^2$

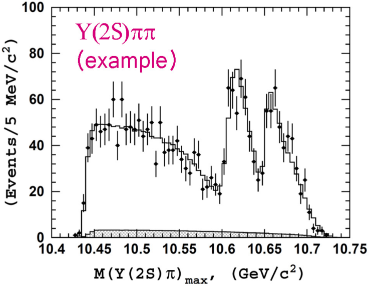
$M_{\pi\Upsilon}^2 = (k_1 + p)^2$

Why is the data @$\Upsilon(5S)$ anomalous?

[Belle Collaboration (2012)]







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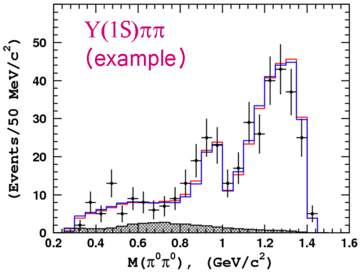
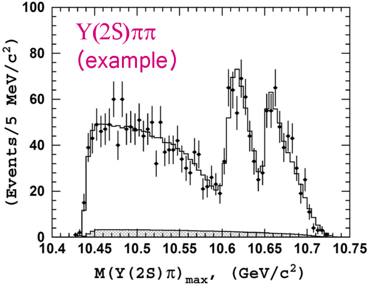
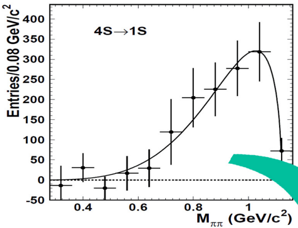
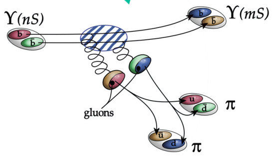






theory works well (multipole exp.) [Brown, Cahn PRL 75] [Voloshin, JETP 75]

Process:



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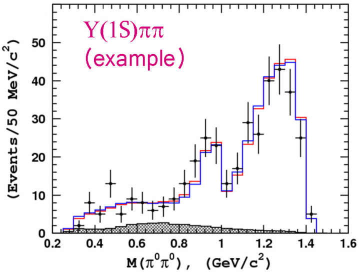

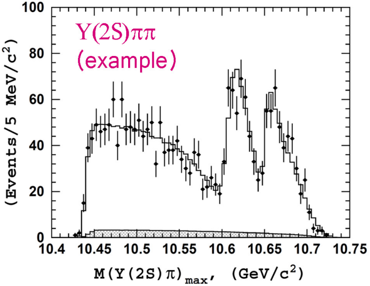

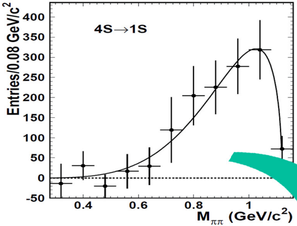

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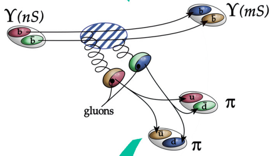

- NO resonant structure
- Zweig forbidden

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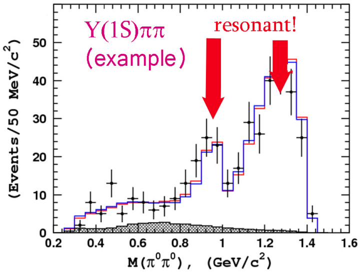
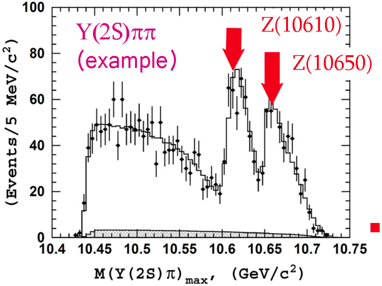


$\Upsilon(1S)\pi\pi$ (example)

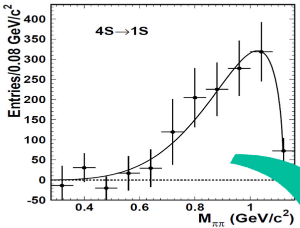
resonant!



$\Upsilon(2S)\pi\pi$ (example)

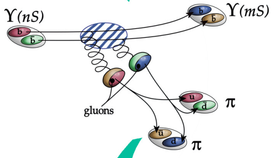
Z(10610)

Z(10650)



theory works well (multipole exp.) [Brown, Cahn PRL 75] [Voloshin, JETP 75]

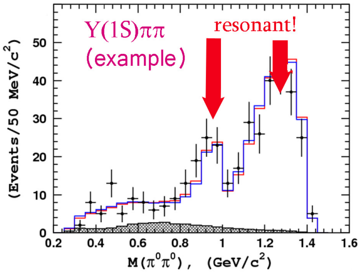
Process:

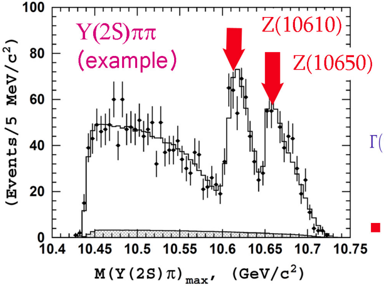


- distinct resonant structure ↯

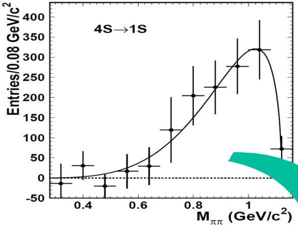
- NO resonant structure
- Zweig forbidden

Why is the data @Υ(5S) anomalous?





[Belle Collaboration (2012)]



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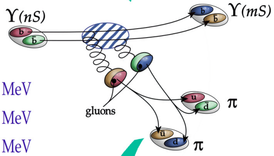

$\Gamma(\Upsilon(2S) \to \Upsilon(1S)\pi\pi) \approx 0.0060$ MeV

$\Gamma(\Upsilon(3S) \to \Upsilon(1S)\pi\pi) \approx 0.0009$ MeV

$\Gamma(\Upsilon(4S) \to \Upsilon(1S)\pi\pi) \approx 0.0019$ MeV

$\Gamma(``\Upsilon(5S)" \to \Upsilon(1S)\pi^+\pi^-) \approx 0.59$ MeV

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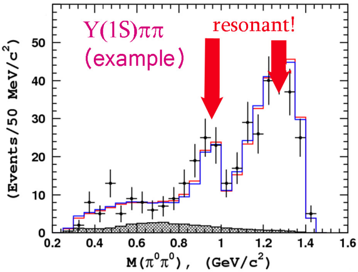

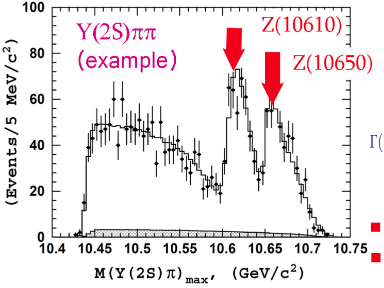

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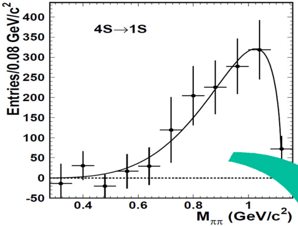

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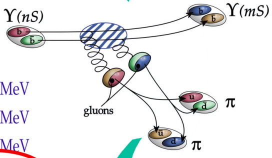

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- distinct resonant structure ϟ
- differs by two orders of Magnitude! ϟ

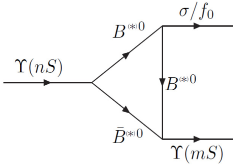
- NO resonant structure
- Zweig forbidden

Tetraquark vs. Rescattering

- Tetraquark & Rescattering: Two rivals in explaining Belle enigma

Tetraquark vs. Rescattering

- Tetraquark & Rescattering: Two rivals in explaining Belle enigma



Tetraquark vs. Rescattering

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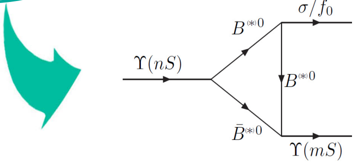
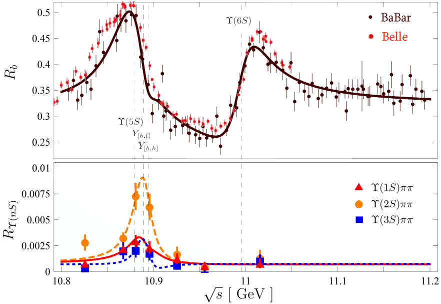


Rough estimate in Rescattering [Meng, Chao, PRD 08] :

$$\Gamma_{\Upsilon(6S)\to\Upsilon(1,2,3S)\pi\pi} \gtrsim \Gamma_{\Upsilon(5S)\to\Upsilon(1,2,3S)\pi\pi}$$

(Problem of approach: introduced ad hoc form factor to suppress phase space enhancement)



Tetraquark vs. Rescattering

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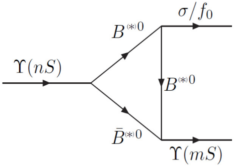

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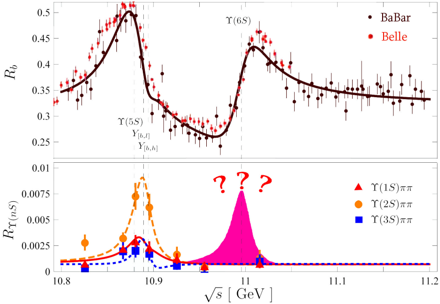
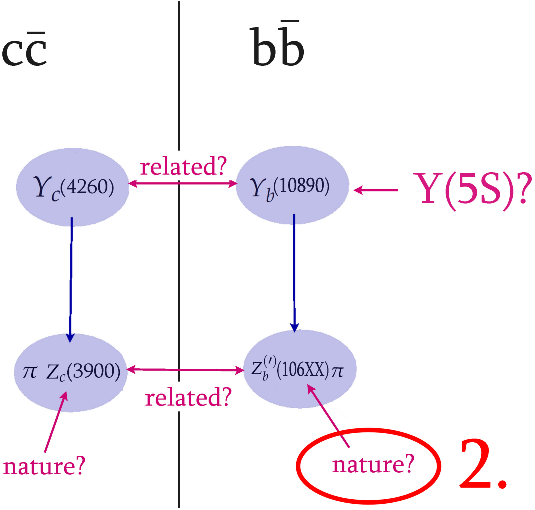


Relation $c\bar{c}$ & $b\bar{b}$



$c\bar{c}$

$b\bar{b}$

$\Upsilon_c(4260)$

related?

$\Upsilon_b(10890)$ ← Y(5S)?

$\pi\ Z_c(3900)$

related?

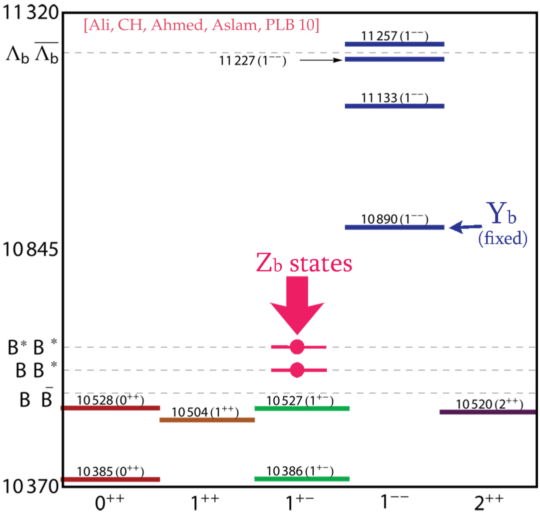
$Z_b^{(\prime)}(106XX)\pi$

nature?

nature?

2.

$[bq][\bar{b}\bar{q}]$ Constituent Model Spectrum



- HQ symmetry motivates fixing
- states are iso-doublets $q = u, d$
- tetraquark Z_b masses do not agree with Belle
- However tetraquarks with mixing & self energy corrections in principle allowed in parts of parameter space [Ali, CH, Wang, PRD 11]

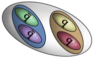
Z_b States: Molecule or Tetraquark?

Molecule

[Bondar, Garmash, Milstein, Mizuk, Voloshin, PRD 11] , [Zhang, Zhong, Huang, PLB 11] , [Voloshin, PRD 11] , [Yang,Ping, Deng, Zong, JPG 11] , [Sun, He, Liu, Luo, Zhu, PRD 11] , …

$$|Z_{b(10610)}\rangle = \left(0_{b\bar{q}} \otimes 1_{\bar{b}q} + 1_{b\bar{q}} \otimes 0_{\bar{b}q}\right)/\sqrt{2}$$

$$|Z_{b(10650)}\rangle = 1_{b\bar{q}} \otimes 1_{\bar{b}q}$$



Tetraquark

[Yang, Ping, Deng, Zong, JPG 11] , [Guo, Cao, Zhou, Chen, 11] , [Ali, CH, Wang, PRD 11] , …

$$|Z_{b(10610)}\rangle = \left(0_{[bq]} \otimes 1_{[\bar{b}\bar{q}]} - 1_{[bq]} \otimes 0_{[\bar{b}\bar{q}]}\right)/\sqrt{2}$$

$$|Z_{b(10650)}\rangle = 1_{[bq]} \otimes 1_{[\bar{b}\bar{q}]}$$

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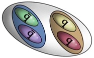
Tetraquark



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↓ Fierz ↓

$$|Z_{b(10610)}\rangle = 1^-_{b\bar q}\otimes 1^-_{q\bar b}$$

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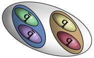
Tetraquark



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$$|Z_{b(10650)}\rangle = (1^{-}_{b\bar{q}} \otimes 0^{-}_{q\bar{b}} + 0^{-}_{b\bar{q}} \otimes 1^{-}_{q\bar{b}})/\sqrt{2}$$

$$Z_{b(10610)} \to B\bar{B}^* + B^*\bar{B}$$

$$Z_{b(10650)} \to B^*\bar{B}^*$$

$$Z_{b(10610)} \to B^*\bar{B}^*$$

$$Z_{b(10650)} \to B\bar{B}^* + B^*\bar{B}$$

Z_b States: Molecule or Tetraquark?

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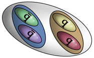
[Bondar, Garmash, Milstein, Mizuk, Volos-
hin, PRD 1
11] , [Volos
Zong, JPG
11] , …

$|Z_{b(10610)}\rangle$ =

$|Z_{b(10650)}\rangle$ =

Tetraquark



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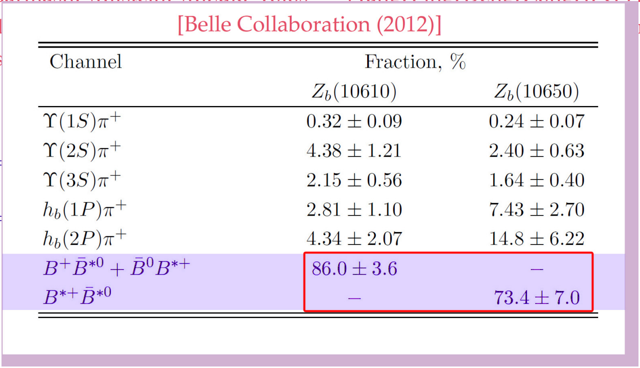
ng, PRD 11] ,

$\otimes\, 0_{[\bar b \bar q]}) / \sqrt{2}$



[Belle Collaboration (2012)]

Channel	Fraction, %	
	$Z_b(10610)$	$Z_b(10650)$
$\Upsilon(1S)\pi^+$	0.32 ± 0.09	0.24 ± 0.07
$\Upsilon(2S)\pi^+$	4.38 ± 1.21	2.40 ± 0.63
$\Upsilon(3S)\pi^+$	2.15 ± 0.56	1.64 ± 0.40
$h_b(1P)\pi^+$	2.81 ± 1.10	7.43 ± 2.70
$h_b(2P)\pi^+$	4.34 ± 2.07	14.8 ± 6.22
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	86.0 ± 3.6	−
$B^{*+}\bar{B}^{*0}$	−	73.4 ± 7.0

~~$|Z_{b(10650)}\rangle = (1^-_{b\bar q} \otimes 0^-_{q\bar b} + 0^-_{b\bar q} \otimes 1^-_{q\bar b}) / \sqrt{2}$~~

✓

$Z_{b(10610)} \rightarrow B\bar{B}^* + B^*\bar{B}$

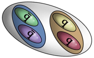
$Z_{b(10650)} \rightarrow B^*\bar{B}^*$

$Z_{b(10610)} \rightarrow B^*\bar{B}^*$

$Z_{b(10650)} \rightarrow B\bar{B}^* + B^*\bar{B}$

Z_b Concluding Remarks

Tetraquark



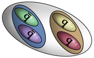
PRO:
nothing special yet

Molecule

PRO:
Close to thresholds (but above)
Explains $B^{(*)}\bar{B}^{(*)}$ decay pattern

Z_b Concluding Remarks

Tetraquark



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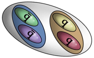


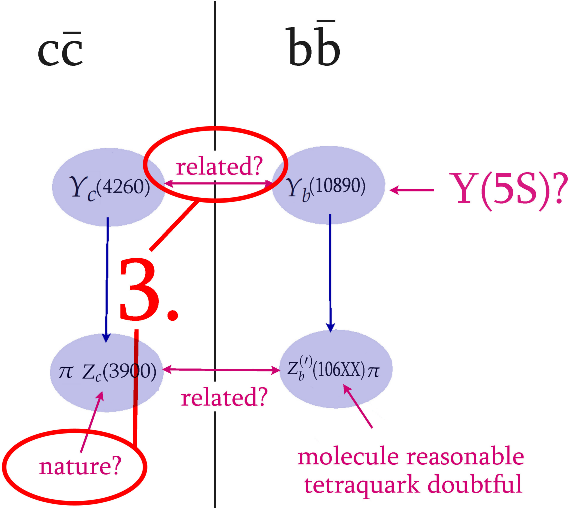
PRO:
nothing special yet

Molecule

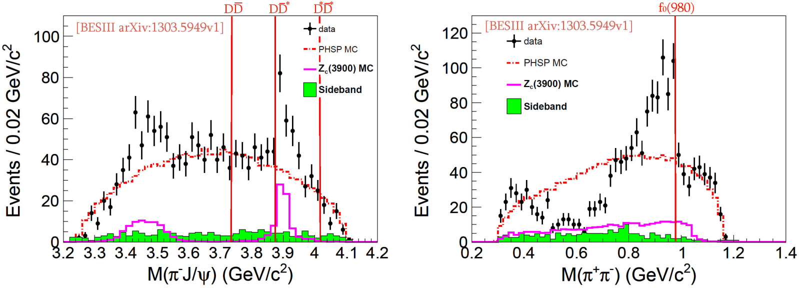
PRO:
Close to thresholds (but above)
Explains $B^{(*)}\bar{B}^{(*)}$ decay pattern

…but then, something unexpected happened: $Z_c(3900)$ …

Relation $c\bar{c}$ & $b\bar{b}$



Surprise from BESIII (3 weeks ago)



- $Y_c(4260) \to J/\psi\pi\pi$ (similar to $Y_b(10890) \to \Upsilon(1S)\pi\pi$)

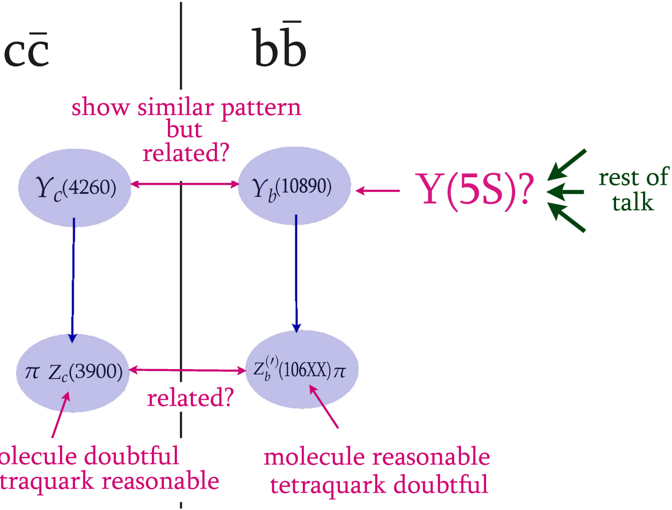
→ $m_{Z_c(3900)} = 3899 \pm 6$ MeV, $\Gamma_{Z_c(3900)} = 46 \pm 22$ MeV, (≈ 4σ above $D\bar{D}^*$ threshold)

Similarities between $Y_b(10890)$ and $Y_c(4260)$:

- both 1^{--}
- constituent model: $m_b - m_c \approx 3333$ MeV
  - → $m_{Y_b(10890)} \approx m_{Y_c(4260)} + 2(m_b - m_c)$ (naive estimate 30 MeV off)
- seen in decay $V\pi\pi$ (V is J/ψ or Υ)
- similar resonant structure $f_0(500, 980)$ in $m_{\pi\pi}$ and $Z_{b,c}$ in $m_{V\pi}$

But: molecule interpretation for Z_c NOT likely

Puzzle



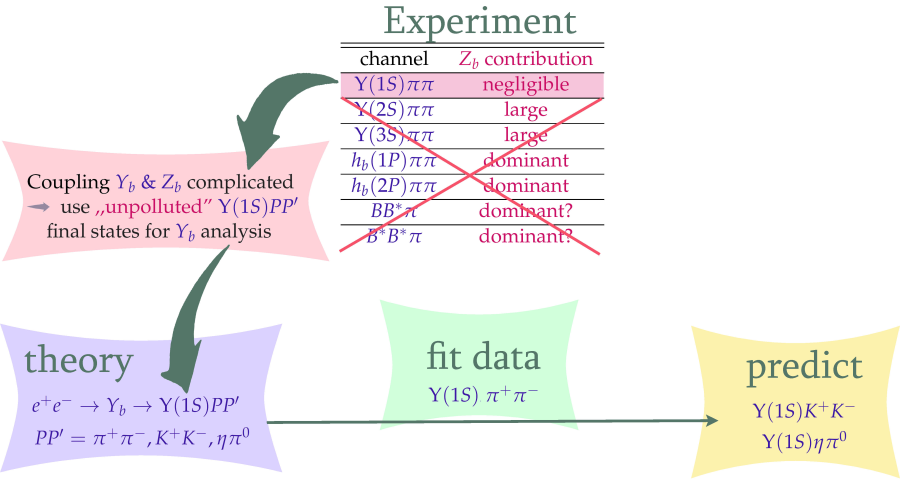
$c\bar{c}$
$b\bar{b}$
show similar pattern
but
related?
$Y_c(4260)$
$Y_b(10890)$
Y(5S)?
rest of
talk
$\pi\ Z_c(3900)$
$Z_b^{(\prime)}(106XX)\,\pi$
related?
molecule doubtful
tetraquark reasonable
molecule reasonable
tetraquark doubtful

Establishing exoticness of Υ_b: Plan A

(isospin)

Plan A

- [Ali, CH, Aslam, PRL 10] [Ali, CH, Mishima, PRL 11] : model dependent assumption: point-like diquarks ➞ isospin effects in e^+e^- production
- isodoublet structure $[bu][\bar{b}\bar{u}]$ and $[bd][\bar{b}\bar{d}]$ seen in different final states?



Experiment

channel	Z_b contribution
$\Upsilon(1S)\pi\pi$	negligible
~~$\Upsilon(2S)\pi\pi$~~	~~large~~
~~$\Upsilon(3S)\pi\pi$~~	~~large~~
~~$h_b(1P)\pi\pi$~~	~~dominant~~
~~$h_b(2P)\pi\pi$~~	~~dominant~~
~~$BB^*\pi$~~	~~dominant?~~
~~$B^*B^*\pi$~~	~~dominant?~~

Coupling Y_b & Z_b complicated
➞ use „unpolluted" $\Upsilon(1S)PP'$
final states for Y_b analysis

theory

$e^+e^- \to Y_b \to \Upsilon(1S)PP'$

$PP' = \pi^+\pi^-, K^+K^-, \eta\pi^0$

fit data

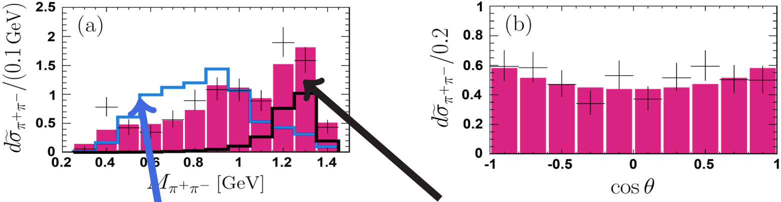
$\Upsilon(1S)\,\pi^+\pi^-$

predict

$\Upsilon(1S)K^+K^-$

$\Upsilon(1S)\eta\pi^0$

Fit to $\sigma(e^+e^- \to Y_b \to \Upsilon(1S)\pi^+\pi^-)$



2^{++} meson $f_2(1270)$

0^{++} tetraquarks $\sigma(500)$ + $f_0(980)$

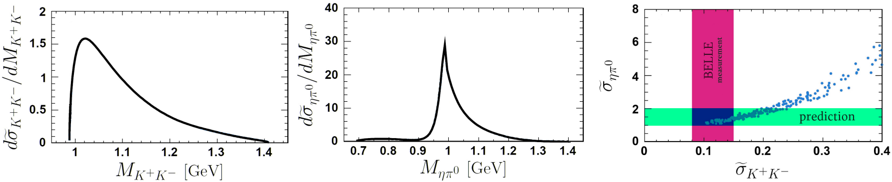
- Fit results, data from [Belle, PRL 08]
- $\chi^2/\text{d.o.f.} = 21.5/15$ → Good agreement with data
- Clear resonance dominance!

($\tilde{\sigma}$: normalized to measurement)

Predictions for $\Upsilon(1S)(K^+K^-, \eta\pi^0)$

Fit determines couplings (assume $SU(3)$ flavor symmetry for couplings $(\sigma(500), f_0(980), a_0(980)) \to PP'$, ['t Hooft, Isidori, Maiani, Polosa, Riquer, PLB 08])

- predictions for spectra:



- Agreement with $\tilde{\sigma}_{K^+K^-} = 0.11^{+0.04}_{-0.03}$ (BELLE)
  - $1.0 \lesssim \tilde{\sigma}_{\eta\pi^0} \lesssim 2.0$ predicted
- Resonance dominance
  - Characteristic shape
    - **Excellent tests (relying on Y_b isodoublet)**

Establishing exoticness of Y_b: Plan B

(hadroproduction)

Spectroscopy above Threshold

channel	spectrum	integrated	Z_b contribution
$\Upsilon(1S)\pi\pi$	✓	✓	negligible
$\Upsilon(2S)\pi\pi$	✓	✓	large
$\Upsilon(3S)\pi\pi$	✓	✓	large
$\Upsilon(1S)KK$	soon?	✓	
$\Upsilon(2S)KK$	not yet	not yet	
$\Upsilon(3S)KK$	not yet	not yet	
$h_b(1P)\pi\pi$	✓	✓	dominant
$h_b(2P)\pi\pi$	✓	✓	dominant
$\Upsilon(1S)\eta\pi^0$	not yet	not yet	
$\eta_b\rho\pi$	not yet	not yet	
$BB^*\pi$	✓	✓	dominant?
$B^*B^*\pi$	✓	✓	dominant?
@$\Upsilon(6S)$	BELLE II	BELLE II	

our prediction

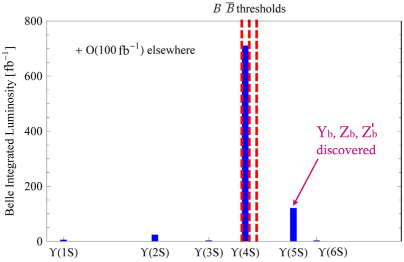
important to confirm exotic state

Spectroscopy above Threshold

channel	spectrum	integrated	Z_b contribution
$\Upsilon(1S)\pi\pi$	✓	✓	negligible
$\Upsilon(2S)\pi\pi$	✓	✓	large
$\Upsilon(3S)\pi\pi$	✓	✓	large
$\Upsilon(1S)KK$	soon?	✓	
$\Upsilon(2S)KK$	not yet	not yet	
$\Upsilon(3S)KK$	not yet	not yet	
$h_b(1P)\pi\pi$	✓	✓	dominant
$h_b(2P)\pi\pi$	✓	✓	dominant
$\Upsilon(1S)\eta\pi^0$	not yet	not yet	
$\eta_b\rho\pi$	not yet	not yet	
$BB^*\pi$	✓	✓	dominant?
$B^*B^*\pi$	✓	✓	dominant?
@$\Upsilon(6S)$	BELLE II	BELLE II	

our prediction

important to confirm exotic state



- multiquark states typically above hadronic thresholds
- few data for $b\bar{b}$ ($c\bar{c}$ advantage ISR & B decays)
- blank area likely full of surprises
- important to understand $b\bar{b}$ & $c\bar{c}$ simultaneously

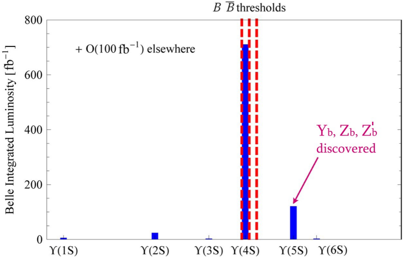
Spectroscopy above Threshold

channel	spectrum	integrated	Z_b contribution
$\Upsilon(1S)\pi\pi$	✓	✓	negligible
$\Upsilon(2S)\pi\pi$	✓	✓	large
$\Upsilon(3S)\pi\pi$	✓	✓	large
$\Upsilon(1S)KK$	soon?	✓	
$\Upsilon(2S)KK$	not yet	not yet	
$\Upsilon(3S)KK$	not yet	not yet	
$h_b(1P)\pi\pi$	✓	✓	dominant
$h_b(2P)\pi\pi$	✓	✓	dominant
$\Upsilon(1S)\eta\pi^0$	not yet	not yet	
$\eta_b\rho\pi$	not yet	no	
$BB^*\pi$	✓	✓	dominant?
$B^*B^*\pi$	✓	✓	ant?
@$\Upsilon(6S)$	BELLE II ??	BELLE II ??	

maybe sooner?

our prediction

important to confirm exotic state



- multiquark states typically above hadronic thresholds
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Spectroscopy above Threshold

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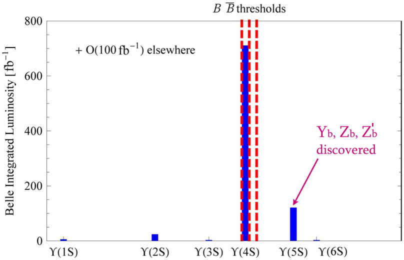

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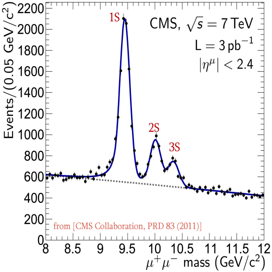
LHCb promising to map uncharted $b\bar{b}$ region including more than $J^{PC} = 1^{--}$

caveat: hadroproduction more complicated than electroproduction

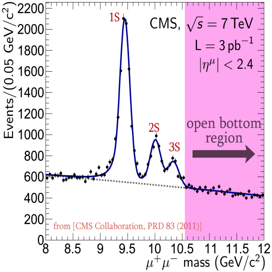
Hadroproduction of Bottomonia



from [CMS Collaboration, PRD 83 (2011)]

- $\mu^+\mu^-$ channel: Common particle detection for bottomonia

Hadroproduction of Bottomonia



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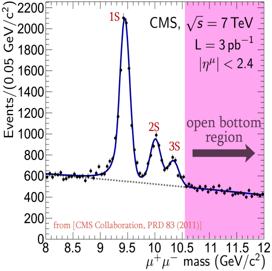

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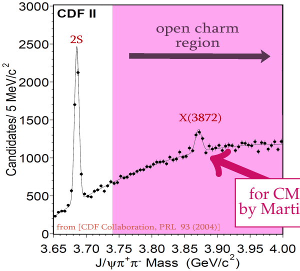

from [CDF Collaboration, PRL 93 (2004)]

for CMS, see poster by Martino Dall'Osso

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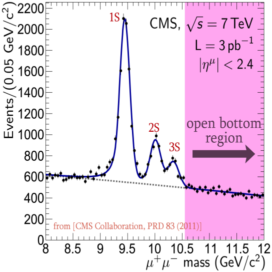

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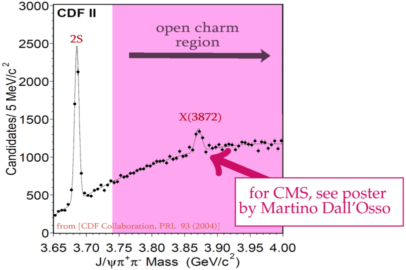

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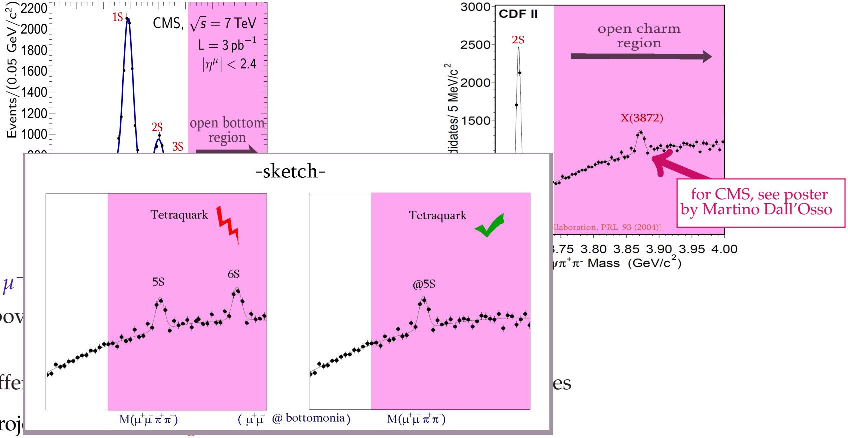
Future project [Ali, CH, Wang] :

Acquire knowledge of bottomonia above hadronic thresholds
(NRQCD, pNRQCD [Brambilla, Pineda, Soto, Vairo, NP 00])

- clarify nature of observed states

Hadroproduction of Bottomonia



for CMS, see poster
by Martino Dall'Osso

- $\mu^+\mu^-$
- Abov
- Differ

es

Future proj

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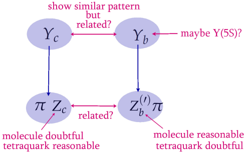
Conclusions

- Mass estimates strongly model dependent - market is messy
- Important puzzle remains:



show similar pattern
but
related?

Y_c

Y_b

maybe Y(5S)?

$\pi\ Z_c$

related?

$Z_b^{(\prime)}\pi$

molecule doubtful
tetraquark reasonable

molecule reasonable
tetraquark doubtful

- Tetraquarks provide a credible explanation for BELLE anomaly @$Y(5S)$
- Predicted spectra for $Y_b(10980)$ provide crucial tests - final proof needed urgently!

Outlook

- Dedicated lattice studies are important
- Radiative decays may be theoretically treatable in QCDSR - need sufficient statistics
- Hadroproduction of bottomonia & tetraquarks very interesting in the near future!

  ➥ heaps of new states expected!

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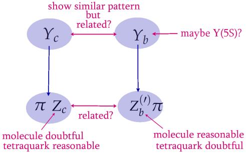

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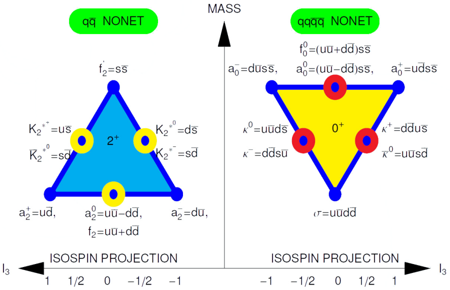
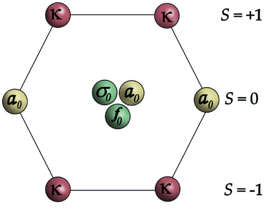
Thank You!

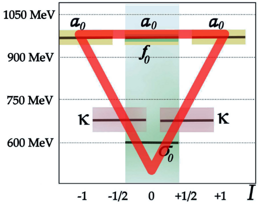
Backup

Constituent Quark Modell and Light States

- Masses for light resonances in constituent model
  - Flavor nonets are arranged as triangles







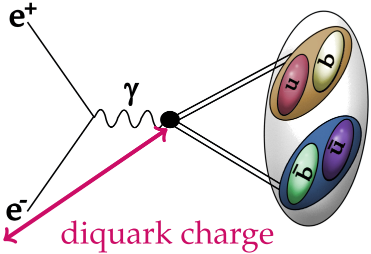
- Tetraquark interpretation in agreement with experiment ['t Hooft, Isidori, Maiani, Polosa, Riquer, PLB 08]

Y_b Production

- Van Royen-Weisskopf formula
  $\Rightarrow \Gamma(1^{--} \rightarrow e^+ e^-)$

Assumption: Point-like diquarks

[Ali, CH, Mishima, PRL (2010)]



diquark charge

$$\Gamma_{ee}(Y_{[b,l/h]}) = \frac{24\alpha^2 Q^2_{[b,l/h]}}{M^4_{Y_{[b,l/h]}}} \kappa^2 \left| R^{(1)}_{11}(0) \right|^2$$

- Suppressed $\mathcal{O}(10)$ vs $\Upsilon(5S)$
- Production ratio: $\Gamma_{Y_{[b,l]}} / \Gamma_{Y_{[b,h]}} = \left(\frac{1-2\tan\theta}{2+\tan\theta} \right)^2$
- Isospin breaking through production

  e.g. $\frac{\sigma_{\Upsilon(1S)K^+K^-}}{\sigma_{\Upsilon(1S)K^0\bar{K}^0}} = \frac{Q^2_{[bu]}}{Q^2_{[bd]}} = \frac{1}{4}$

$L = 0$ NR States

$$\Gamma^0 = \frac{\sigma_2}{\sqrt{2}}$$

$$\Gamma^i = \frac{1}{\sqrt{2}}\sigma_2\sigma_i$$

$$\begin{aligned}
|0_Q, 0_{\bar{Q}};\ 0_J\rangle &= \frac{1}{2}\,(\sigma_2) \otimes (\sigma_2) \\
|1_Q, 1_{\bar{Q}};\ 0_J\rangle &= \frac{1}{2\sqrt{3}}\left(\sigma_2\sigma^i\right) \otimes \left(\sigma_2\sigma^i\right) \\
|0_Q, 1_{\bar{Q}};\ 1_J\rangle &= \frac{1}{2}\,(\sigma_2) \otimes \left(\sigma_2\sigma^i\right) \\
|1_Q, 0_{\bar{Q}};\ 1_J\rangle &= \frac{1}{2}\left(\sigma_2\sigma^i\right) \otimes (\sigma_2) \\
|1_Q, 1_{\bar{Q}};\ 1_J\rangle &= \frac{1}{2\sqrt{2}}\varepsilon^{ijk}\left(\sigma_2\sigma^j\right) \otimes \left(\sigma_2\sigma^k\right)
\end{aligned}$$

Two states with $J^{PC} = 0^{++}$:

$$\begin{aligned}
\left|0^{++}\right\rangle &= |0_Q, 0_{\bar{Q}};\ 0_J\rangle \\
\left|0^{++\prime}\right\rangle &= |1_Q, 1_{\bar{Q}};\ 0_J\rangle
\end{aligned}$$

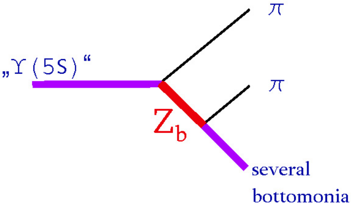
Three states with $J = 1$:

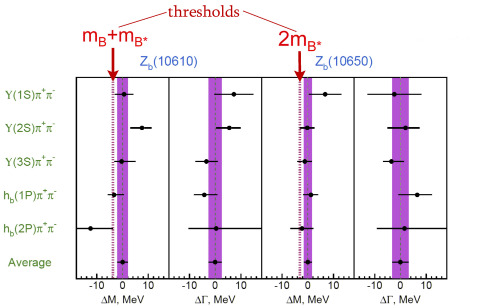
$$\begin{aligned}
\left|1^{++}\right\rangle &= \frac{1}{\sqrt{2}}\left(|0_Q, 1_{\bar{Q}};\ 1_J\rangle + |1_Q, 0_{\bar{Q}};\ 1_J\rangle\right) \\
\left|1^{+-}\right\rangle &= \frac{1}{\sqrt{2}}\left(|0_Q, 1_{\bar{Q}};\ 1_J\rangle - |1_Q, 0_{\bar{Q}};\ 1_J\rangle\right) \\
\left|1^{+-\prime}\right\rangle &= |1_Q, 1_{\bar{Q}};\ 1_J\rangle
\end{aligned}$$

Z_b Masses by Belle

[Belle Collaboration, PRL 12]

measured in:





$Z_b(10610)$ **M=10607.2±2.0 MeV** **$Z_b(10650)$** **M=10652.2±1.5 MeV**

- Masses close to threshold:

No need for tetraquark scenario

- However tetraquarks with mixing & self energy corrections

[Ali, CH, Wang, PRD 11]

➞ in principle allowed in parts of parameter space